MONITORING BRAIN INJURY WITH TSALLIS ENTROPY

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Abstract- **Nonextensive entropy measure, Tsallis Entropy (*TE*), was undertaken to monitor the brain injury after cardiac arrest. EEG of human and experimental injury model of rats are investigated. In both conditions *TE* decreases in bad physiological functional outcome. As the brain recovers from injury, the *TE* will also gradually return to normal level. Meanwhile, *TE* also shows good sensitivity to different grades of asphyxic injury. This method provides a novel real time brain injury indicator and may be a useful in developing a diagnostic monitoring tool.**
Keywords: **electroencephalogram, generalized entropy, brain injury**

I. INTRODUCTION

About 60% of those persons who are successfully resuscitated after cardiac arrest subsequently die of extensive brain injury every year in the United States [1]. Real time monitoring the brain asphyxia state after resuscitation of cardiac arrest is a critical clinical problem. However, there are no current approved real time objective assessments used to monitor brain injury. Clinicians are expecting a "brain-holter" to detect and monitor the cerebral function, which may require the practical and effective quantitative EEG (qEEG) methods that extract the primary brain feature information from the EEG time series.

In recent years, information measures including the traditional Shannon entropy have been shown to be effective in dealing with complex signals[2]. Shannon entropy is based on the Boltzmann-Gibbs (BG) statistical mechanics and standard thermodynamics, which is restricted for additive (extensive) systems. Over the last few years, it has been realized that Shannon entropy fails to yield testable results for systems with long-range interactions, long-term memory effects or abrupt changes like spikes and bursts, [3]. Thus, it is reasonable to look for alternative information measures that may be better adapted to those nonextensive systems. A nonextensive (nonadditive) entropy now called Tsallis entropy (*TE*) was postulated by Tsallis[4]. In the past ten years *TE* has proved successful in describing systems with long-range interactions, multifractal space-time constraints or long-term memory effects. In this study we attempt to apply this kind of novel entropy measure in monitoring the EEG of injured brain.

II. TSALLIS ENTROPY MEASURE

The classical Shannon Entropy[5] is measured by the distribution of probabilities $p = \{p_i\}$:

$$SE = -\sum_{i=1}^{M} p_i \ln(p_i) \qquad (1)$$

allowing for $0 \ln 0 = 0$, where p_i is the probability of finding the system in the i^{th} microstate with $0 \le p_i \le 1$ and $\sum_{i=1}^{M} p_i = 1$. M is the total number of microstates. This formalism (1) has been shown to be restricted to the domain of validity of the BG statistics, which describes a system in which the effective microscopic interactions and the microscopic memory are of short range.

One type of generalized entropy, named Tsallis entropy, has proved effective as a measure of nonextensive system. Tsallis entropy is defined as:

$$TE = \frac{1 - \sum_{i=1}^{M} p_i^q}{q-1} \qquad (2)$$

When $q \to 1$, $p_i^{q-1} = e^{(q-1)\ln(p_i)} \sim 1 + (q-1)\ln(p_i)$, Eq. (2) recovers to the usual Shannon entropy in (1). The nonextensivity of Tsallis entropy is:

$$TE(A \cup B) = TE(A) + TE(B) + (1-q)TE(A)TE(B) \qquad (3)$$

Considering $0 \le p \le 1$ in (2), $p_i^q \le p_i$ for $q>1$ and $p_i^q \ge p_i$ for $q<1$, hence q>1 and q<1 will respectively correspond to the frequent and rare events. Meanwhile, the EEG signals in brain injury are complex, punctuated for example by frequent burst activity during the recovery of asphyxic injury. The source of EEG is generally accepted as synaptic potentials from the cortical neurons, while the source of bursting is probably the deep nuclei such as the thalamic and reticular thalamic neurons. There is very likely an ongoing interaction between the two generators through thalamocortical and cortico-thalamic tracts. Thus, EEG in our study demonstrates mixing of long-range interactions suggesting the use of a nonextensive entropy description. In our work we justify the superextensive hypothesis with the choice of $q > 1$ based on the previous research on EEG.[2]

III. MATERIALS

We demonstrated the *TE* in both the experimental EEG of animals and the clinical human EEG. We obtained experimental EEG recordings from anesthetized rats for studying the information evolution in brain rhythms following asphyxic injury. Asphyxic cardiac arrest and

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resuscitation protocol approved by the animal Care and Use Committee of the Johns Hopkins Medical Institutions was performed as modified from Katz and colleagues[6]. The experimental protocol is as follows:

Wistar rats (300±25 g) were randomly assigned to surgical graded asphyxia of 3, 5 min and hypoxia preconditoning (n=5 per group). The animal subject was monitored for 10 minutes baseline and 5 minutes anesthetic (halothane) washout followed by 3 or 5 minutes global asphyxia and its subsequent recovery. For the preconditoning rats, 25 min hypoixa was conducted at about one hour before the global aspyxia. Two channels of EEG using sub-dermal needle electrodes (Grass Instruments, Quincy, MA) in right and left parietal areas, one channel of ECG and one channel of arterial pressure were recorded continuously before the insult, during the insult, and for about 5 hours of recovery. The signals were digitized using the data acquisition package CODAS (DATAQ Instruments INC., Akron OH). Sampling frequencies of 250Hz and 12bit A/D conversion were used. Before applying the TDE method, the EEG was filtered (0.5~30Hz) and the ECG artifacts removed[7].

Human EEG was recorded from: patient A: high grade injury with long cardiac arrest (CA) time (20 min) and long cardiopulmonary resuscitation (CPR) time (30min), didn't survive in the end; patient B: low grade injury with short CA time (4 min) and short CPR (5min) and survived; patient C: normal volunteer as a reference.

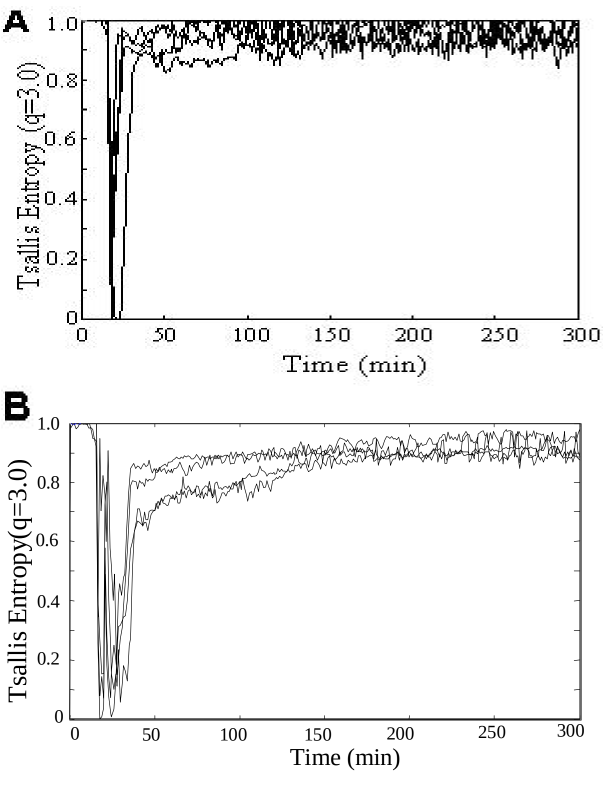

Fig. 1. (A) Global entropy trends for the EEG from several animals subjects in the 3 min cardiac arrest injury group, (B) Global entropy for several animals in the 5 min injury group. The sharp drop correspond to the injury incident followed by recovery over the next 5 hr indicating partial restoration.

IV. RESULTS

We applied the *TE* to the experimental EEG data from the 3 min and 5 min asphyxia cohorts. Each 5-hour EEG record was analyzed minute by minute. Within each minute segment we estimated the *TE* with (2) with the parameter q=3.0 and amplitude partitions M=30; for each rat, the entropy results are normalized by the mean *TE* of the baseline EEG. Fig. 1A and Fig. 1B respectively correspond to the 3 min and 5min asphyxia group.

In Fig. 2 we analyzed the human EEG selected between O1 and O2 channels. The parameters used in *TE* are the same as those Fig. 1.

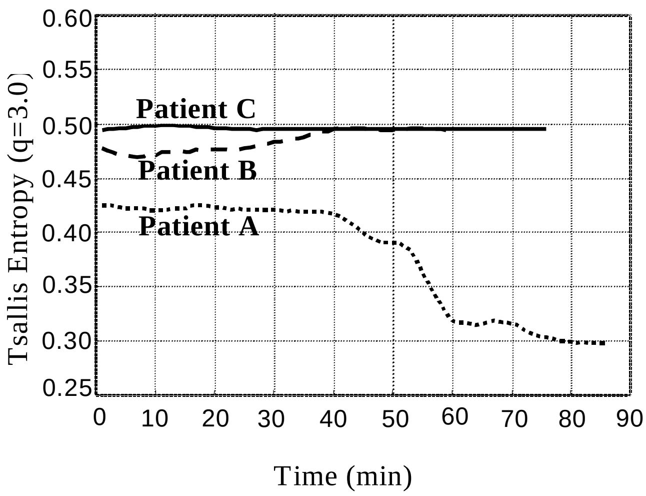

Fig. 2. Tsallis entropy (q=3.0) analysis of O1-O2 channel EEG of human. patient A: high grade injury with long CA time (20 min) and long CPR time (30min), didn't survive in the end; patient B: low grade injury with short CA time (4 min) and short CPR (5min) and survived; patient C: normal volunteer.

V. DISCUSSION

The traditional linear methods of the EEG analysis (spectral analysis, AR modeling) are based on the assumption that the observations of the electrical field of the brain are of stationary random processes. For a variety of physiological reasons, EEG rhythms in disease may require nonlinear approaches. The nonlinear theory offers novel ways to characterize the behavior of complex yet deterministic systems. Since the mid-1980s various methods derived from nonlinear dynamics have been applied to biosignal processing. The nonlinear dynamics methods employ a set of metric parameters such as correlation dimensions, Lyapunov exponents, Kolmogorov and approximate entropies, and are usually based on the distances between points in an appropriate embedding space. Calculations of these parameters require large data sets. Meanwhile, the stationarity of the signal to be analyzed is

usually taken for granted. However, this condition is actually not satisfied in most of the cases while dealing with EEG signals [8]. Previous research has also shown that the EEG is not only high dimensional nonlinear but also nonstationary[9]. The electrical activity of the brain is usually time-variable, nonstationary and irregular, especially in pathological conditions such as epileptic seizures or hypoxic-asphyxic injury.

Tsallis entropy is based on the generalized BG statistical mechanics. The parameter q indicates the nonextensive degree of a system. The different q values correspond to different statistical mechanicss. The appropriate choice of the entropic index q is significant but still remains to be studied. Literature has pointed to the role of q in the entropy computation for EEG studies [10]. In our study it is hypothesized that the brain's electrical activity is represented by superextensive ($q>1$) system. Interactions within the brain are the foundation of its higher function. The interactions and information transmission across the brain cortex have been reported [11]. In our experiments, although the origins of EEG are cortical, the origin of the bursts is thought to be thalamic residing in deep brain area [12]. Interactions occur through thalamocortical and cortico-thalamic tracts. Experiments have shown the long-term thalamo-cortical interactions [13]. Therefore, it is safe to say that the data analyzed represent at least two channels A and B between which there is information transmission, which means there exists mutual information between A and B so that $TE(A \cup B) < TE(A) + TE(B)$. Comparing with (3) we get $q>1$. In our case, we refer to our previous empirical choice for brain injury description with $q=3$[14].

VI. CONCLUSIONS

The nonextensive entropy provides a novel statistical description of the brain rhythms during asphyxic injury and recovery. Even though the recovery mechanism of brain injury is highly complex, the *TE* seems to expose the nature of brain EEG in the form of reduction during the bad physiological function outcome. The reduction level and recovery rate of *TE* are also consistent with brain physiological states. These trends may prove to be useful in developing a diagnostic monitoring tool.

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